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EARLY DATA FROM A REAL-TIME COCHLEA.(U)
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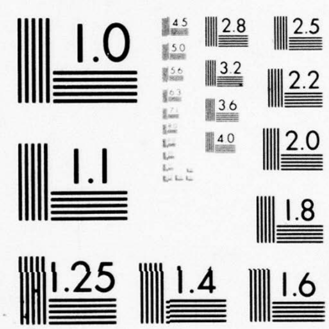

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EARLY DATA FROM A REAL-TIME COCHLEA

A Final Report for the
September, 1976 - September, 1977 Period

by

Victor W. Bolie
Principal Investigator

Technical Report No. EE-249(77)AFOSR-497-1
Work Performed Under Contract No. AFOSR-77-3110

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and

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EARLY DATA FROM A REAL-TIME COCHLEA

By Victor W. Bolie

Background

Automatic coding of speech sounds in real time, with minimum dependence on voice pitch and individual speaker characteristics, is a key requirement in the coming development of verbally responsive machines. Ordinary telephone conversation using phonemes and words in scrambled order reveals sound overlaps (three _vs_ free), spellings (one _vs_ won), and meanings (train _vs_ train), which have been tolerated for generations. Pending the evolution of intelligently tolerant machines, some sort of restricted language will need to be developed for early applications, e.g., computers programmed by voice instruction.

It goes without saying that no algorithm for word recognition or sentence interpretation should be burdened with separating phonemes which can be well isolated and identified by immediate "front-end" conversion of the speech signal. The artificial ear used in the research reported here (and elsewhere; see Tables 1 and 2) has appeal from the viewpoint of "naturalness." In particular, it has been anticipated that the 6-millisecond propagation time of the basilar membrane is important in the identification of plosive bursts (and in the separation of male _vs_ female voices).

Hardware/Software Problems

The system previously assembled for the study of prolongable phonemes proved adequate for that purpose (see Appendix A). From a reading of the HP instruction manuals and I/O specifications available at that time, it was expected that with the acquisition of the HP "burst read" tape, the same system could be used to collect data on the plosive transients. A major delay in the research resulted when it was found that the burst-read mode is actually limited to an uninterrupted string of only 255 data bytes. This restricted the system capability to a time-segment capture of only 16 milliseconds of fine-structure data, followed by a software gap of at least 40 milliseconds to initiate the next burst.

The unavoidable restructuring of the I/O part of the system was accomplished (on a hurried prototype basis) by detailed assembly of 3072 bytes of external memory, inserted between the sampler/ADC unit and the I/O service unit. The result of this effort was an extension of the high-speed read capability to an uninterrupted time segment of 1300 milliseconds.

The other features of the HP-9830 (reliability, memory size, flexibility, and low cost) still make it a good machine for low-budget ASR research--especially if ways can be found to slow down the input data rate without losing significant information carried in the speech signal.

High-Speed Results

With the system modified as described above, a software program was arranged so that data collection on a 1300-MS segment of continuous speech could be initiated by merely pressing a "start" key. The data train (stored first in the external memory at real-time rate, and ingested later at computer-time rate) consisted of 64 consecutive sweeps of the 16 output taps of the cochlea, giving a string of 1024 8-bit words. The output of each cochlear tap was then plotted to visualize the voice-related changes in the velocity profile of the basilar membrane vibrations.

The speech used was that of a seasoned male voice speaking at a normal rate with normally varying inflection. The results for the 8 syllabic sequences:

"Automatic"
"Speech"
"Recognition"
"Computerized"
"Studies"
"Of Cochlear"
"Transformed"
"Phonemes"

are shown in Figures 1 through 8, respectively. In each illustration, the rms velocity of the basilar membrane at a given distance (2, 4, 6, ..., 32 millimeters) from the stapes is plotted as a function of time.

As expected, it is seen that the portion of the basilar membrane close to the stapes (e.g., the 2 and 4 mm traces) respond most strongly to the high frequency (hiss-like) sound components. In most of the records, there appear to be moderate degrees of correlation between neighboring traces, which would tend to dispel the need for a cochlea of more than 16 outputs.

Segments of momentary silence are particularly evident in words like "speech," as demonstrated by Figure 2. Rise times and decay times of the various traces also appear to be significant. Further studies of these and other transients will be required to extract additional features needed for automatic speech recognition.

Table 1. *Chronological List of Publications*

Date	Author	Title[c]	Proceedings
May 1968[a]	Bolie, V. W.	The Ear as a Sound Analyzer	IEEE Region 6 Conf. Rec. (Portland)
Nov. 1969[a]	Bolie, V. W.	Experiments in Machine Learning	U.S. Copyright A114279
April 1970[a]	Bolie, V. W.	CAD Cochlear Design Refinements	*SWIEECO Record* (Dallas)
July 1970[a]	Lake, O. L.[d]	Computer Analysis of Speech	OSU Ph.D. Thesis (Bolie Supv.)
Mar. 1971[a]	Bolie, Baker,[d] and Fristoe	Active Network Audio Filter Bank	Journ. Audio Engr. Soc.
April 1971[a]	Bolie, Fristoe and Baker[d]	Effects of Pitch on Phoneme Spectra	SWIEECO Record (Houston)
May 1971[a]	Bolie and Ledbetter	Newer Design of an Analog Cochlea	Proc. Circuit Theory Symp. (Denver)
June 1971[a]	Baker, J.E.[d]	Speech Signal Reduction Experiments	OSU Ph.D. Thesis (Bolie, Supv.)
Feb. 1973	Bolie, V. W.	Feature Vector Distillation Method	Proc. Com. Sci. Conf. (Columbus)
Dec. 1973	Colclaser, R.A.	Microelectronic Audio Filter Bank	Proc. Asilomar Conf. (Pacific Grove)
Feb. 1976	Bolie, V. W.	Cochlear Design Optimization	Proc. ACM Conf. (Anaheim)

[a] Developed prior to actual starting date of USAFOSR Grant No. 72-7178.

[b] Supported by USAFOSR Grant No. 72-2178.

[c] Titles shortened for convenience

[d] Currently Lt. Col. and Col., USAF.

Table 2. Chronological List of Reports to USAFOSR

Date	Author	Title*	Report No.
Aug. 1972	Bolie, V.W.	First-Year Studies of Speech	EE-198(72)AFOSR-222
Mar. 1973	Bolie, V.W.	Acoustic Neurology Summary	EE-202(73)AFOSR-222
July 1973	DeVries, R.C.	Pattern Recognition Software	EE-206(73)AFOSR-222
Sep. 1973	Bolie, V.W.	Second-Year Studies of Speech	EE-218(73)AFOSR-222-2
Nov. 1973	Knudsen, H.K.	Speech Sampler for the PDP-8/E	EE-220(73)AFOSR-222-3
Dec. 1973	Colclaser, R.A.	Hybrid Microelectronic Filter Bank	EE-221(73)AFOSR-222-3
Aug. 1974	Bolie, V.W.	*Third-Year Studies of Speech*	USAFOSR Grant No. 72-2178C
Aug. 1974	Cordaro, J.T.	Speech Recognition Programs	EE-223(74)AFOSR-222-3
Aug. 1974	Bolie, et al.	AD/DA Interface for the IBM 1620	EE-224(74)AFOSR-222-3
Feb. 1975	Bolie, V.W.	Computer Optimization by CAD	EE-227(75)AFOSR-222-3
Sep. 1975	Bolie, V.W.	Fourth-Year Studies of Speech	EE-231(75)AFOSR-222-3
Sep. 1976	Bolie, V.W.	Fifth-Year Studies of Speech	EE-239(76)AFOSR-222-4

*Titles shortened for convenience.

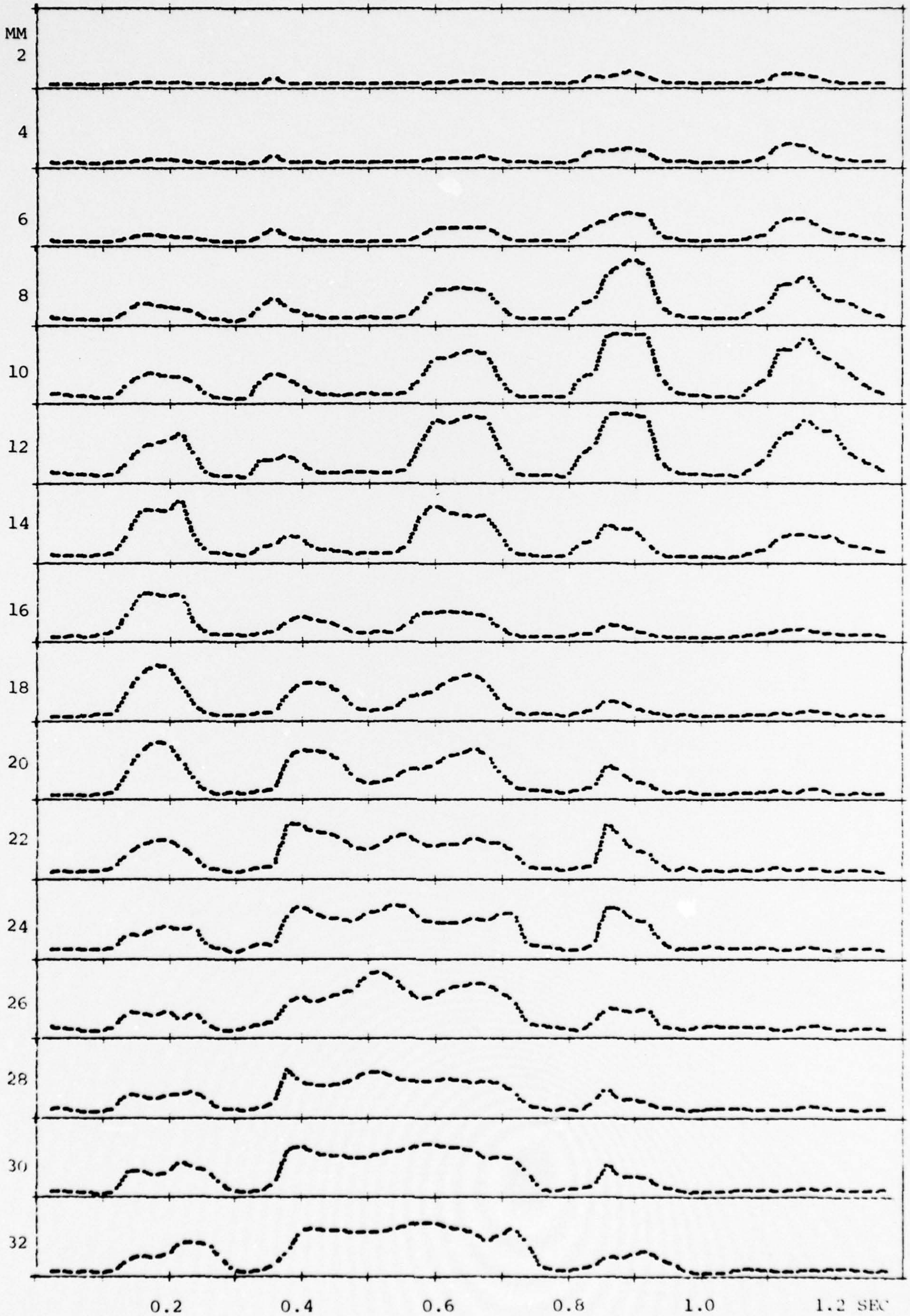


Figure 1. PHONEME SEQUENCE: --AUTOMATIC--

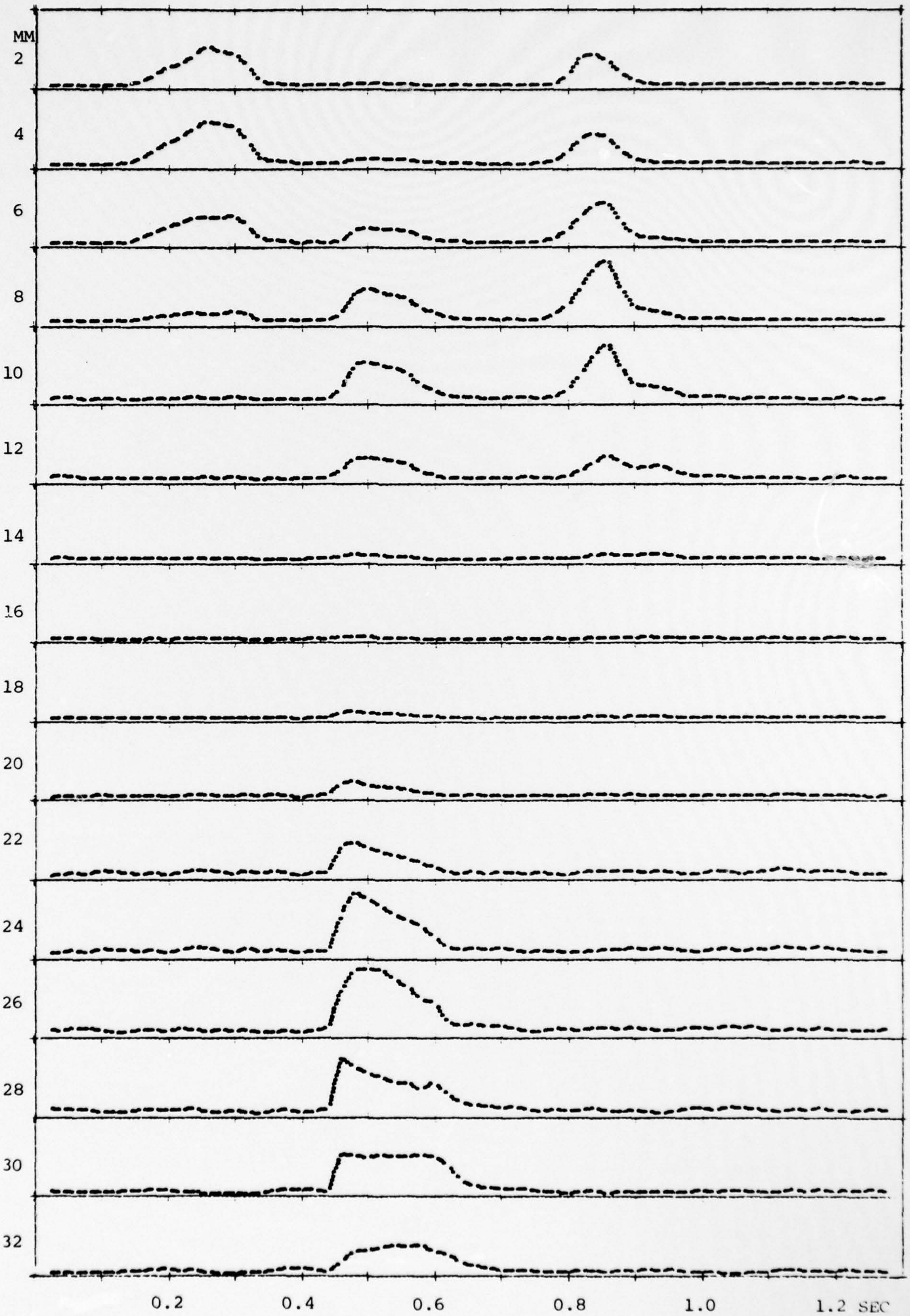


Figure 2. PHONEME SEQUENCE: --- SPEECH ---

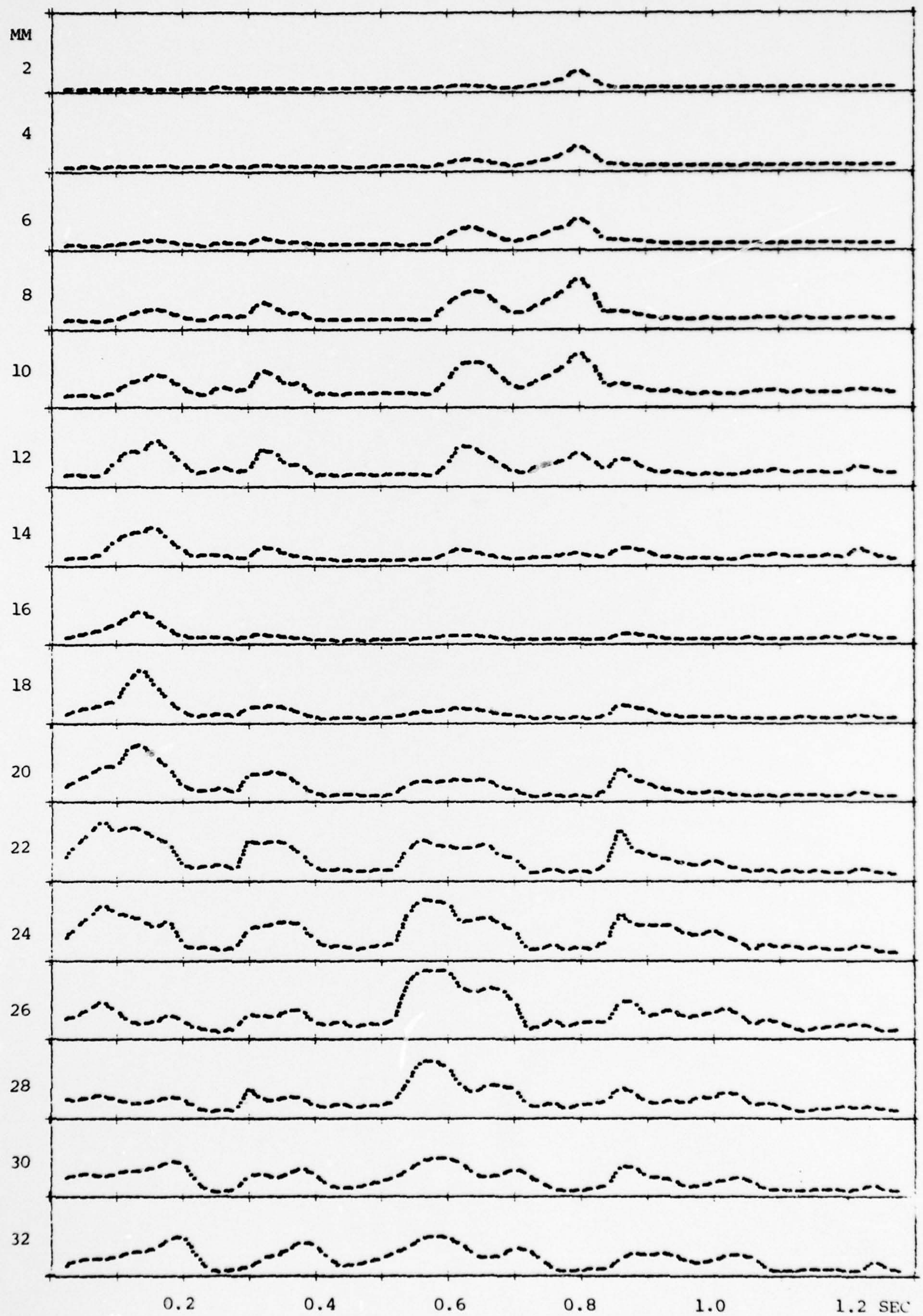


Figure 3. PHONEME SEQUENCE: -RECOGNITION-

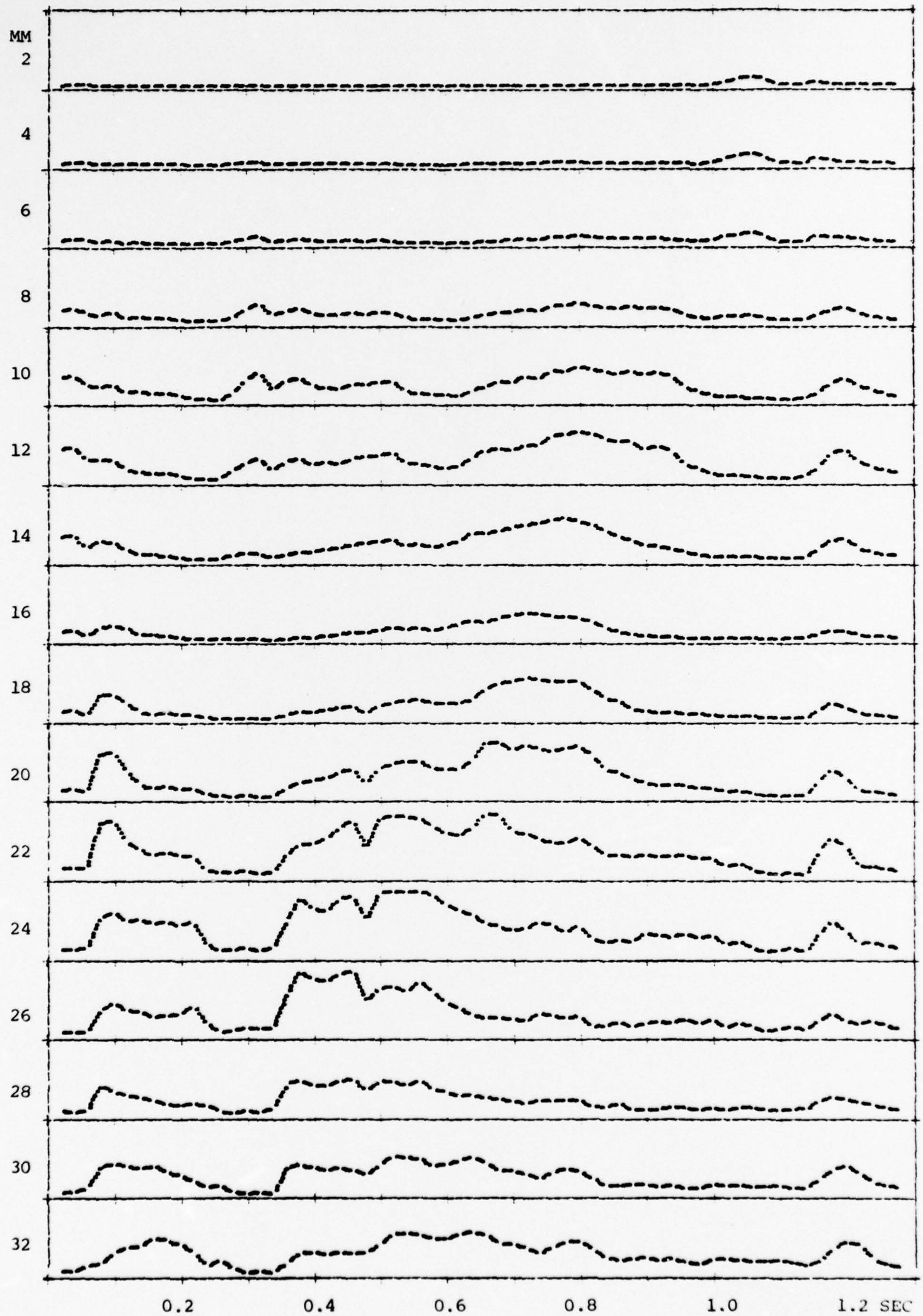


Figure 4. PHONEME SEQUENCE: --COMPUTERIZED--

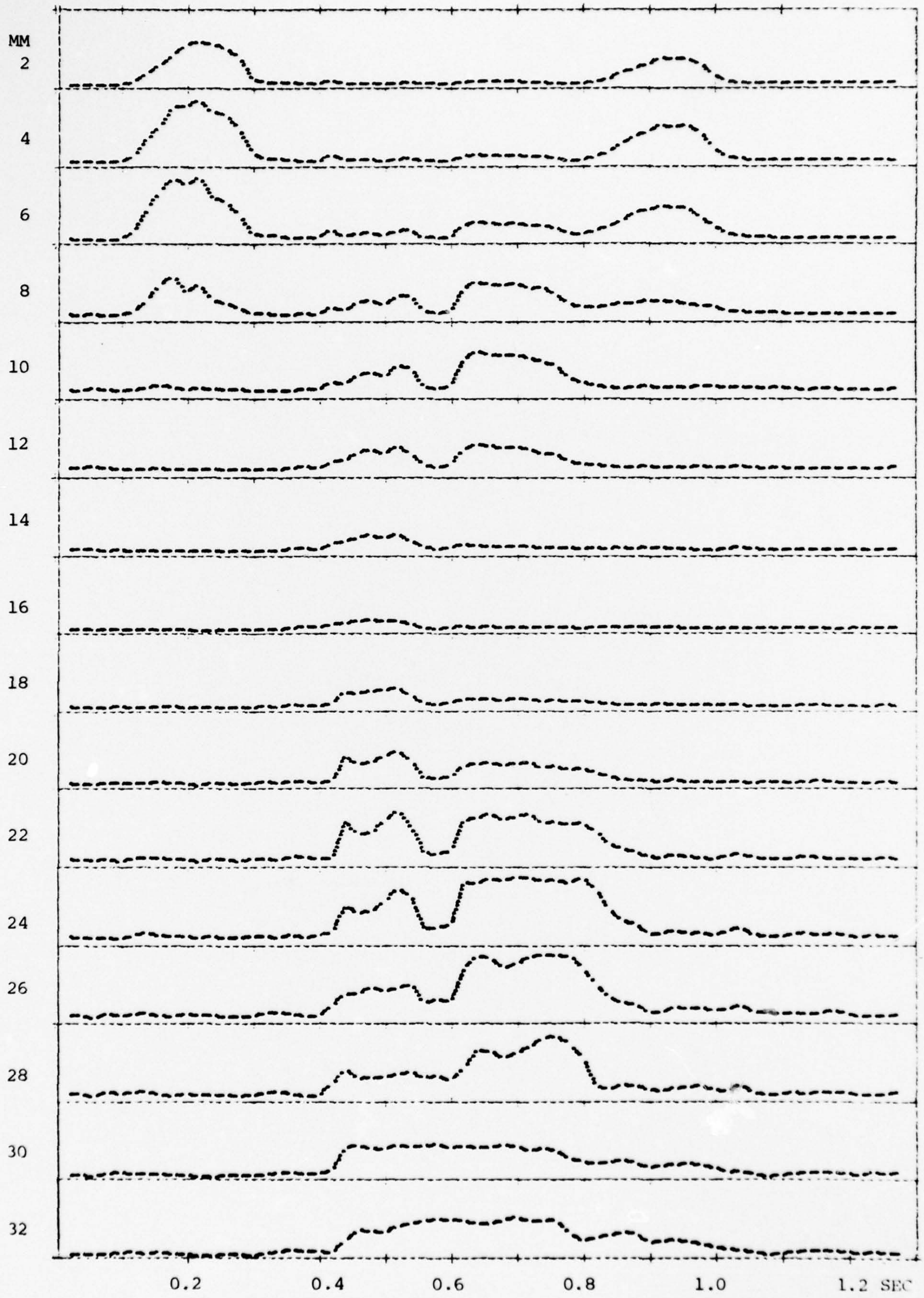


Figure 5. PHONEME SEQUENCE: --- STUDIES ---

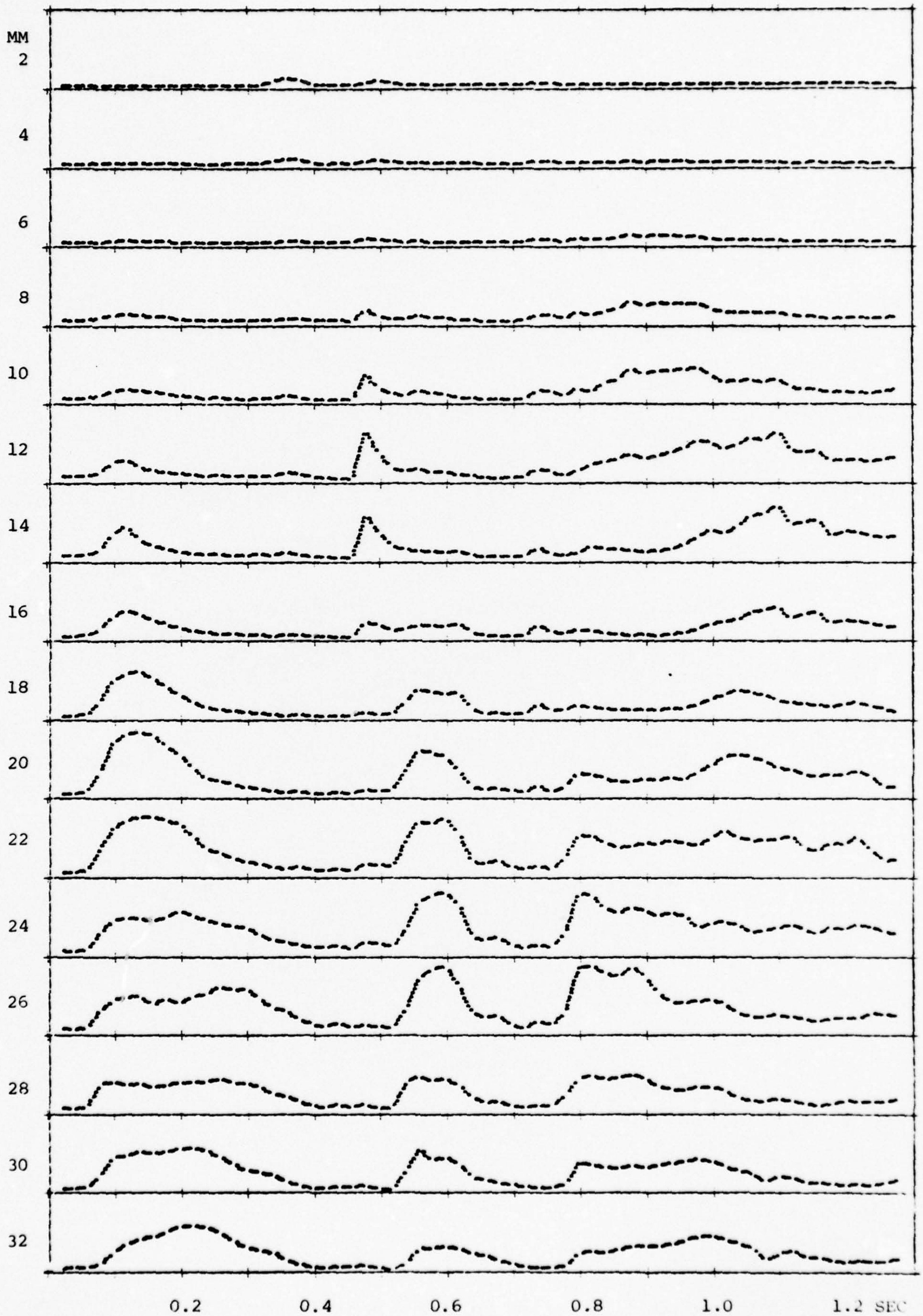


Figure 6.- PHONEME SEQUENCE: --OF COCHLEAR--

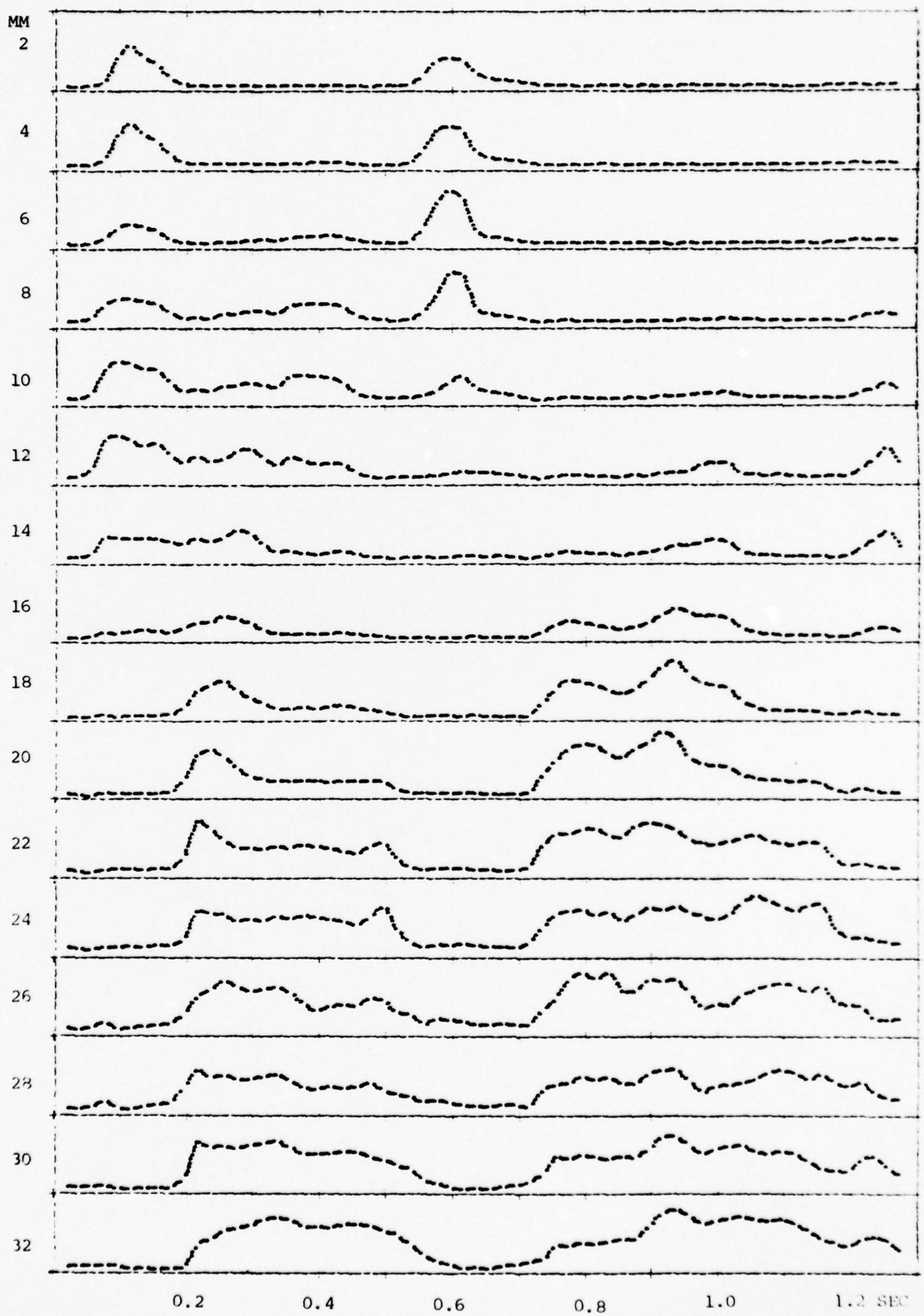


Figure 7. PHONEME SEQUENCE: --TRANSFORMED--

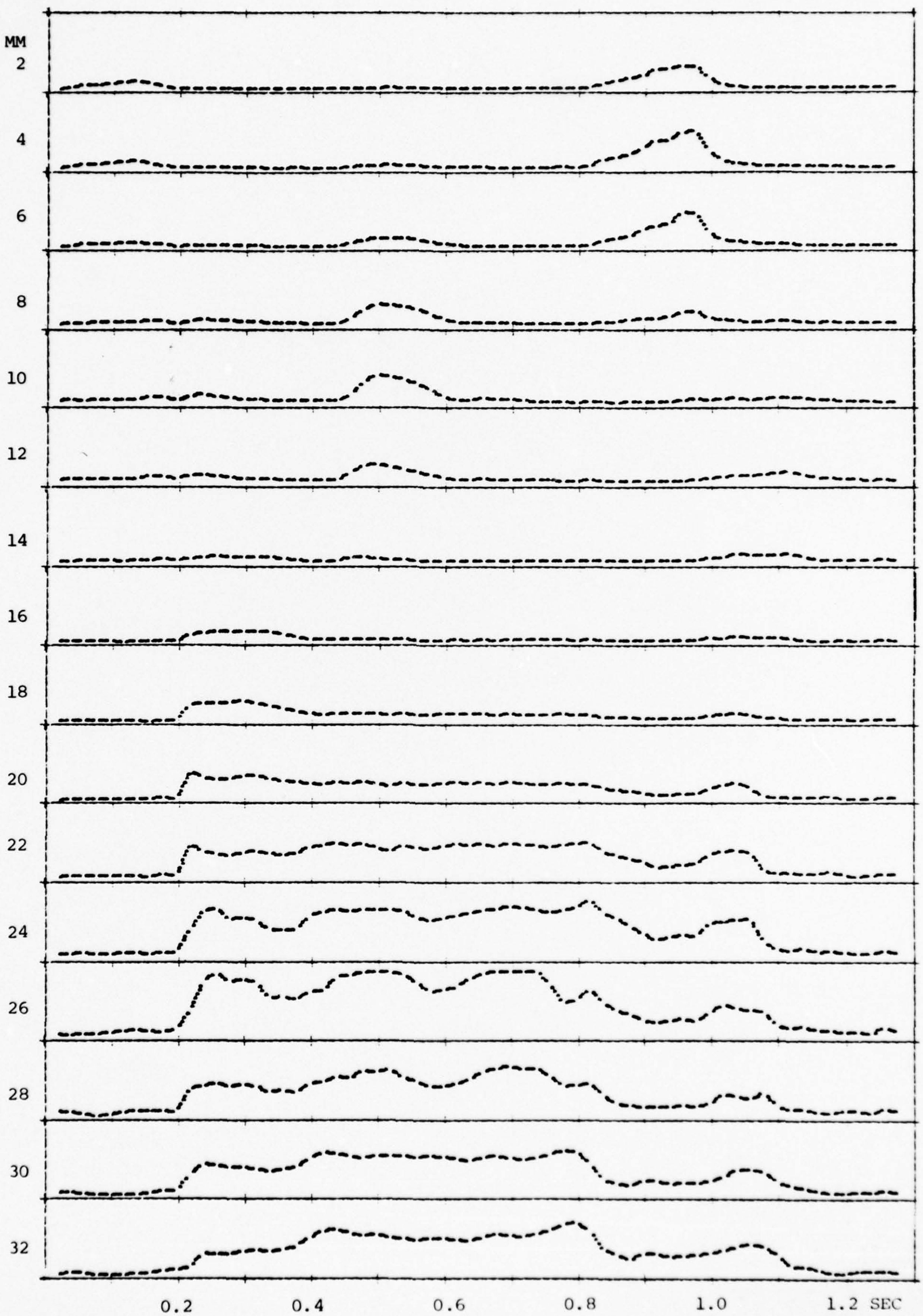


Figure 8. PHONEME SEQUENCE: ---PHONEMES---

APPENDIX A

The Computer-Coupled Artificial Ear

and Some Preliminary Test Results

The Computer-Coupled Artificial Ear

and Some Preliminary Test Results

by V. W. Bolie

The system described elsewhere[1] and summarized by Figures A1 - A5 was tested using the speech sounds identified by Tables A1 - A3. Twelve samples of each sound were captured in the data acquisition and stored on the tape to give a total file of 12 x 21 = 252 cochlear-transformed sounds for training and challenge tests. In loading these phonemes, the unvoiced sounds (4 out of 21) were held steady, and for the voiced sounds (17 out of 21), the pitch was varied in a sing-song manner. The 12 samples of each sound were used to develop 21 reference vectors and 21 tolerance vectors, which were stored as a condensate of the training.

All 252 phoneme samples were then submitted in sequence as challenges to the recognition algorithm[2, 3] and the resulting 252 response vectors were stored for later study of errors and threats. Figure A6 shows the average response vector (a horizontal row in the chart) for any given sound challenge. Fortunately, the largest number in each row falls on the diagonal of this 21 x 21 matrix. The greatest consistent threat appears to be that of the "OU" against the "LL" sound, and the safest sounds appear to be the unvoiced ones (SS, FF, KH, SH).

The 252 response vectors were analyzed further with respect to recognition dangers. For this purpose a measure of hazard was constructed, using the formula,

$$H(E,I) = \frac{B(E,E) + B(E,I)}{A(E,E) - A(E,I)}, \text{ for all } I \neq E,$$

in which A(E,I) is the element in Row E and Column I of the response-vector matrix shown in Figure A6, and in which B(E,I) is the average deviation of the 12 contributions to that element. Each row of the resulting "hazard matrix" was then searched to find the greatest hazard value. The various phonemes were then ranked in ascending order of this value. The results are listed in Table A4, together with the actual recognition errors found from

a trivial search for the largest element in each of the 252 response vectors. As expected, the most errors occur where the computed hazard values are greatest. For more detail, the nature of perception errors are listed in Table A5, where it is seen that practically all of the perception errors are recoverable in the "second-choice" responses.

A pleasant surprise was a finding of high consistency in the first moment of the cochlear response to a given phoneme, irrespective of pitch. This is illustrated in Table A6 in which the maximum value, minimum value, average, and standard deviation of the first moment for each phoneme is listed. Thus, even though the FF sound has a nearly pure noise appearance on the oscilloscope, it has a very well defined cochlear first moment value (75.6 $\pm$ 2.1).

REFERENCES

1. Bolie, V. W. "Computer Optimization of Cochlear Design Parameters," Tech. Rep., USAFOSR Grant No. 72-2178, Feb., 1975.

2. Bolie, V. W. "Feature Vector Distillation Method," Proc. Computer Science Conf., Columbus, Ohio, 1973.

3. Bolie, V. W. "Experiments in Machine Learning," the University of New Mexico Book Store, Albuquerque, New Mexico, 1977.

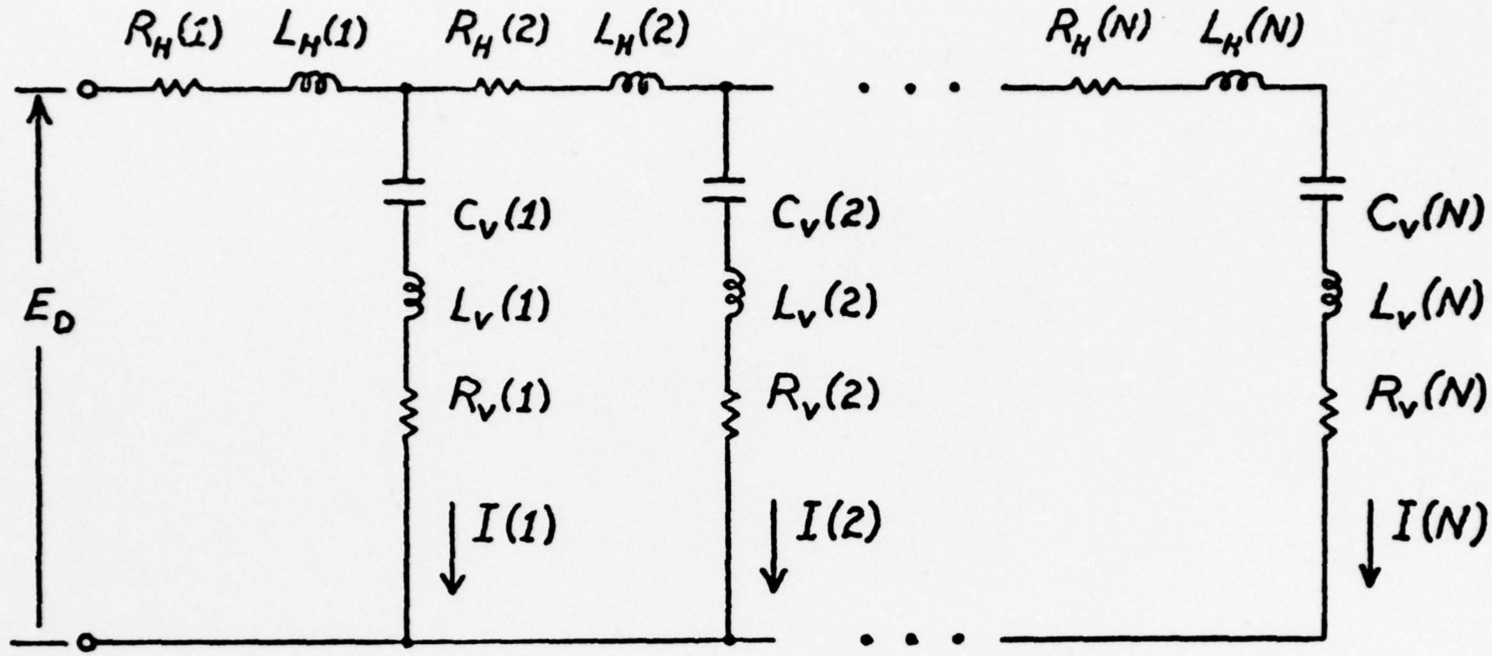


Figure A1. Network Structure of the Analog Cochlea

$$F(K) = (55\sqrt{2})\cdot 2^{P} \quad \text{where } P = 7\cdot(N-K)/N$$

$$R_V(K) = RV \quad \text{for all } 1 \leq K \leq N$$

$$R_H(K) = RH \quad \text{for all } 1 \leq K \leq N$$

$$L_H(K) = (Q_H\cdot RH)/(2\pi\cdot F(K))$$

$$L_V(K) = (Q_V\cdot RV)/(2\pi\cdot F(K))$$

$$C_V(K) = \{(Q_V\cdot RV)\cdot(2\pi\cdot(K))\}^{-1}$$

$$N = 84$$

N = Total number of sections in analog cochlea

ED = Driving voltage applied to input of first section

IR = Reference milliamperes for I(K) membrane velocity

DT = Total propagation delay-time for 100-Hz input

Figure A2. Equations of the Analog Cochlea

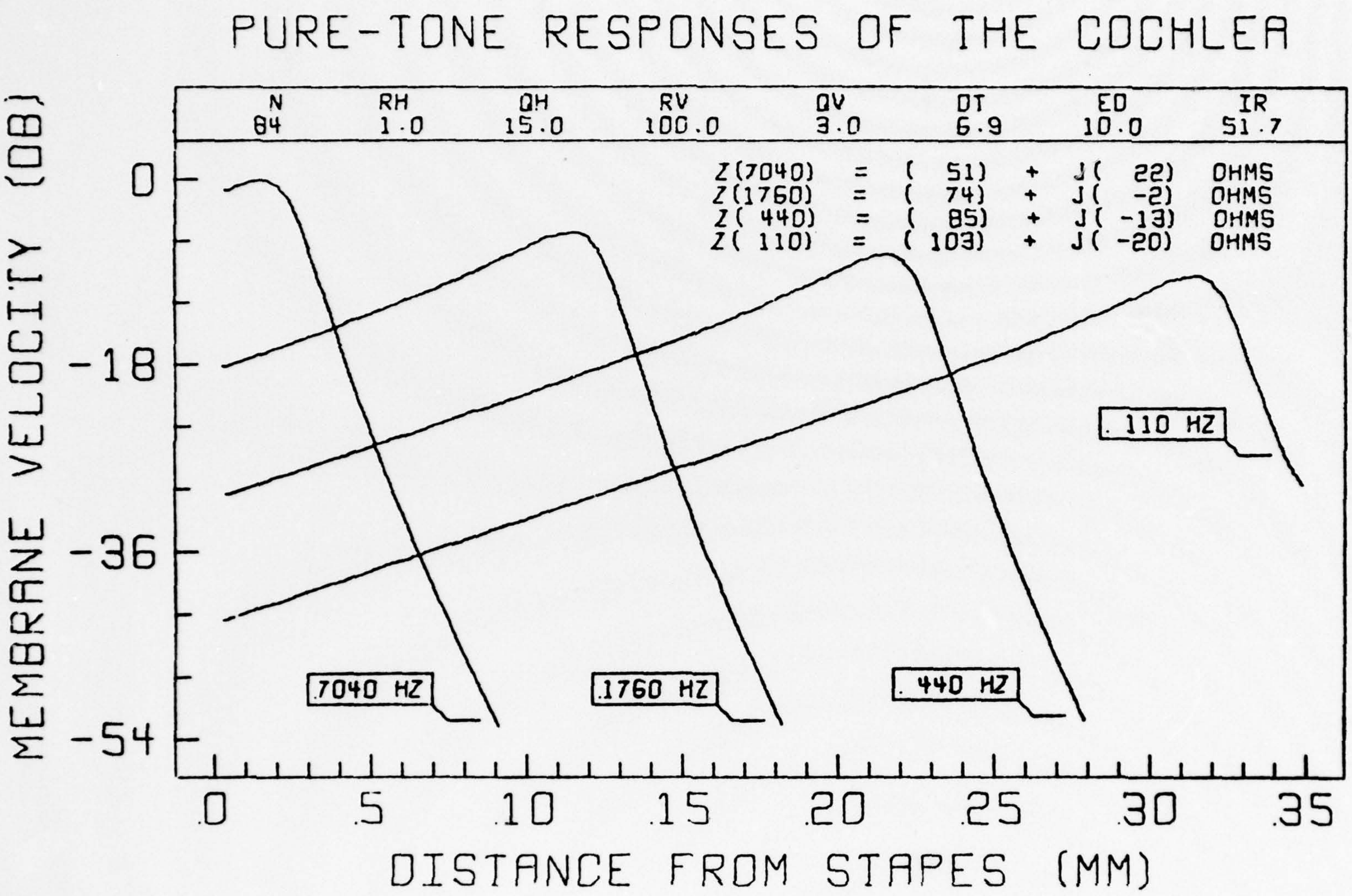
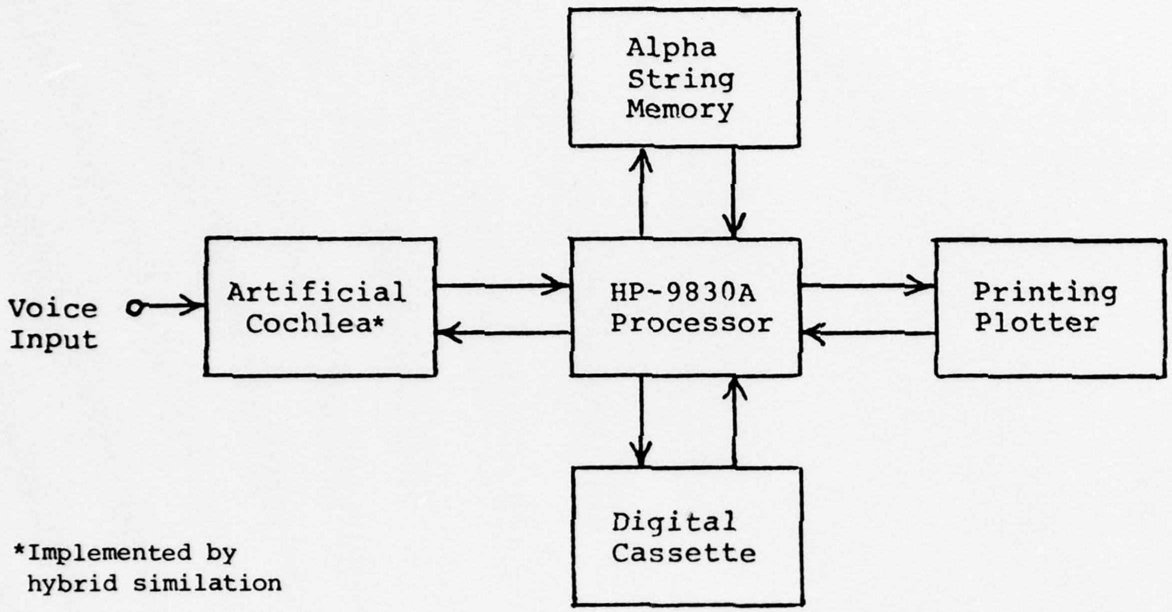
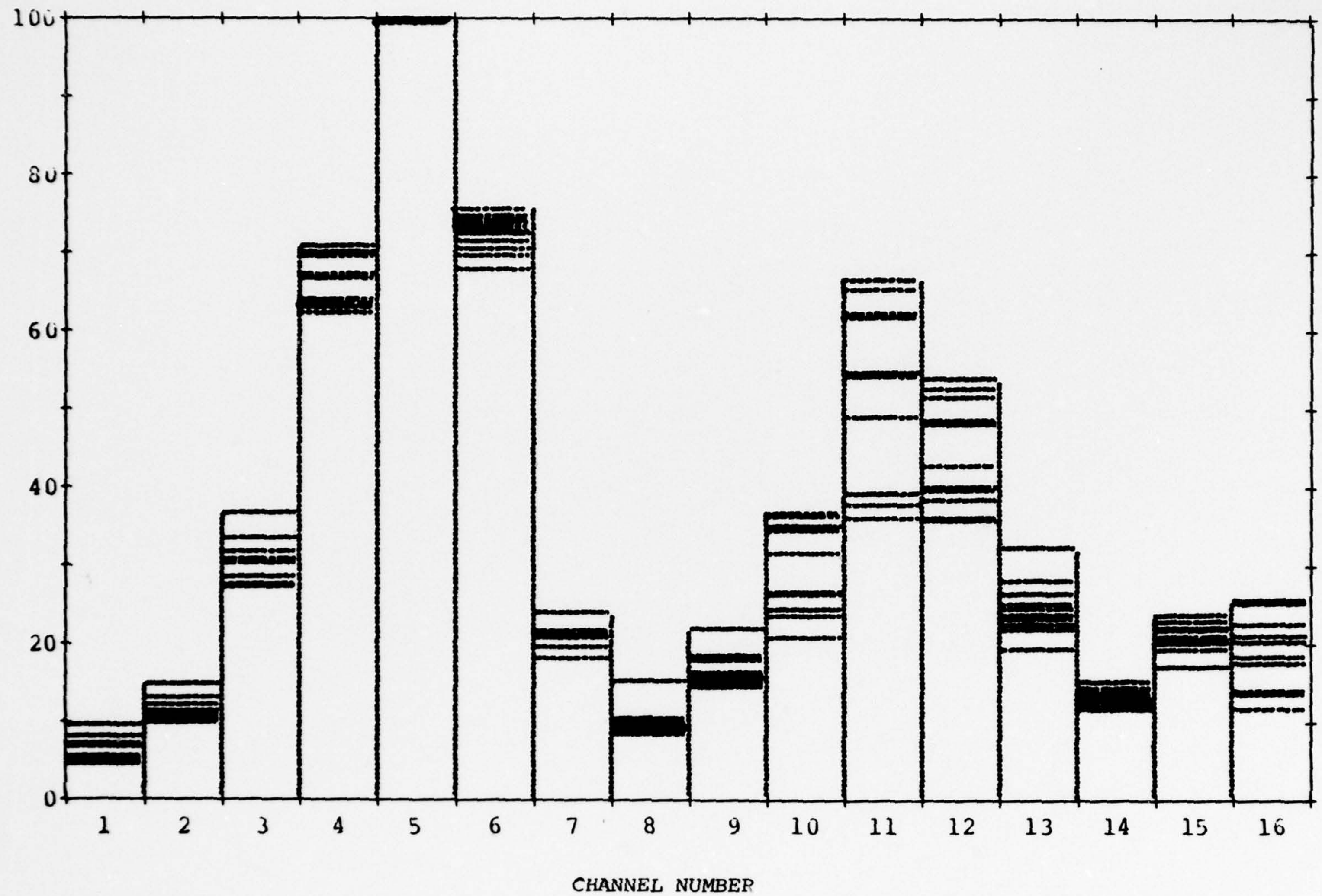


Figure A3. Pure-Tone Responses of the Analog Cochlea



*Implemented by
hybrid similation

Figure A4. Computer-Coupled Artificial Ear



RESPONSE TO THE PHONEME 'AY'

Figure A5. Cochlear Output for a Typical Speech Sound
(Multiple Traces Show Effect of Pitch Changes)

Strength of Identification

Phoneme Actually Voiced	OH	EE	EH	SS	AA	ZZ	AY	FF	OU	LL	KH	AH	RR	OO	AW	SH	VV	II	ZH	UH	NN
OH	59	7	7	4	12	9	6	6	14	6	13	12	13	12	10	5	13	12	4	19	14
EE	4	56	11	3	13	13	18	4	18	9	5	7	11	3	5	3	24	6	4	10	5
EH	8	17	56	3	30	12	32	6	17	8	9	12	11	5	6	5	17	8	4	16	7
SS	8	11	5	67	7	22	6	9	11	5	8	7	6	7	5	6	10	13	6	10	8
AA	7	10	18	2	54	10	17	4	18	7	7	21	13	5	8	3	16	7	4	12	8
ZZ	4	11	6	4	8	54	6	3	17	8	4	8	8	4	5	2	18	10	6	9	6
AY	5	26	25	3	20	12	55	6	18	8	7	9	11	4	5	4	19	7	4	13	6
FF	10	14	12	7	13	11	16	64	11	5	15	8	7	6	5	21	12	9	4	15	6
OU	4	12	6	2	12	14	7	3	53	36	4	11	35	5	12	2	28	8	5	8	8
LL	4	13	6	2	10	14	7	2	53	56	4	9	34	4	10	2	33	7	5	7	8
KH	16	12	13	5	17	10	13	13	12	6	59	9	9	7	6	14	13	10	4	20	9
AH	9	6	6	2	15	10	6	3	18	7	5	55	19	9	15	2	14	9	4	11	16
RR	5	8	6	2	12	12	6	3	39	15	4	12	54	5	12	2	24	8	4	8	10
OO	18	7	5	3	11	10	6	4	18	8	8	16	18	60	18	3	13	11	5	12	36
AW	8	7	6	2	14	11	6	3	25	12	5	27	23	12	57	2	15	9	5	9	18
SH	12	15	16	7	16	10	21	26	12	6	19	8	8	6	5	66	12	9	4	16	7
VV	3	13	7	2	11	14	8	2	29	16	4	8	20	3	7	2	53	7	4	8	7
II	5	7	4	3	7	14	5	3	12	6	3	8	7	5	5	2	13	55	17	14	9
ZH	4	8	4	2	6	14	5	2	12	7	3	7	7	4	4	2	13	29	57	12	7
UH	9	7	8	3	11	10	7	4	11	5	6	10	8	5	4	4	12	11	5	53	7
NN	14	6	5	2	12	11	6	3	18	8	6	23	16	29	18	3	14	11	5	12	55

Figure A6. Quality of Post-Cochlear Pattern Recognition

Table A1. International Phonetic Alphabet

1. [æ] as in "bat"
2. [e] as in "ate"
3. [ɛ] as in "ten"
4. [i] as in "beet"
5. [I] as in "bit"
6. [ɑ] as in "got"
7. [O] as in "go"
8. [ɔ] as in "bawl"
9. [u] as in "boot"
10. [U] as in "book"
11. [ʌ] as in "but"
12. [ər] as in "burr"

13. [l] as in "let"
14. [r] as in "rat"
15. [ω] as in "wet"
16. [j] as in "you"

17. [m] as in "met"
18. [n] as in "net"
19. [ŋ] as in "sing"
20. [f] as in "fall"
21. [h] as in "he"
22. [s] as in "see"
23. [v] as in "vote"
24. [z] as in "zoo"
25. [ʃ] as in "shoe"
26. [θ] as in "thin"
27. [ð] as in "then"
28. [ʒ] as in "azure"

29. [dʒ] as in "joy"
30. [tʃ] as in "chew"
31. [b] as in "bin"

32. [d] as in "did"
33. [g] as in "get"
34. [k] as in "kill"
35. [p] as in "put"
36. [t] as in "top"

Table A2. Listing of the Prolongable Phonemes in the English Language[a]

Ident Number	Alpha Description[b]
1	OH
2	EE
3	EH
4	SS
5	AA
6	ZZ
7	AY
8	FF
9	OU
10	LL
11	KH
12	AH
13	RR
14	OO
15	AW
16	SH
17	VV
18	II
19	ZH
20	UH
21	NN

---

[a]Omitted because of out-of-context indistinguishability are TH (thin *vs* fin), DH (this *vs* vis), and the MM and NG sounds rum *vs* run *vs* rung).

[b]The listed sequence of 21 sounds are those contained in the sentence "Oh, yes, as a full car wash vision."

Table A3. Phoneme Structure of Typical Words

Phoneme Sequence[1]	English Equivalent
RR TH	Earth
SS UH NN	Sun
MM OO NN	Moon
RR II VV RR	River
OO SH UH NN	Ocean
SH AW RR	Shore
OO EH DH RR	Weather
SS UH NN EE	Sunny
RR AY NN	Rain
SS NN OH	Snow
AH EE SS	Ice
SS EE LL II NG	Ceiling
NN AW RR TH	North
SS AH OO TH	South
LL EH VV LL	Level
AA ZZ II MM OU TH	Azimuth
EH LL EH VV AY SH UH NN	Elevation
RR AY NN ZH	Range
FF EE OO SS EH LL AH ZH	Fuselage
OO II NG	Wing
AY LL RR AH NN	Aileron
NN OH ZZ	Nose
KH AA NN UH NN	Cannon
FF LL AA KH	Flak
MM AH EE NN	Mine
RR AH EE FF LL	Rifle
SS LL II NG	Sling
EH RR OH	Arrow
RR UH SH EE UH	Russia
FF RR AA NN SS	France
II ZZ RR AY LL	Israel
RR OH MM	Rome
KH AH EE RR OH	Cairo
MM AH EE AA MM EE	Miami
AH RR MM EE	Army
NN AY VV EE	Navy
MM UH RR EE NN	Marine
EH RR	Air
FF AW RR SS	Force
MM II LL II SH UH	Militia
RR OH LL	Roll
SS KH OO EE ZZ	Squeeze
KH RR UH SH	Crush
SH UH VV	Shove
SS OO KH	Soak
TH RR OH	Throw

[1] The equalities TH = FF, DH = VV, and MM = NG = NN are made automatically as this 2-column dictionary is loaded into memory.

Table A4. Hazard Ranking[1] of Perceptions

Rank	Sound	Hazard	Errors in 12 Challenges
1	UH	0.109	0
2	KH	0.133	0
3	SH	0.143	0
4	SS	0.149	0
5	FF	0.191	0
6	AH	0.233	0
7	AA	0.242	0
8	OH	0.245	0
9	AY	0.248	0
10	II	0.258	0
11	AW	0.267	0
12	ZZ	0.272	0
13	EH	0.283	0
14	ZH	0.325	0
15	OO	0.350	1
16	NN	0.381	0
17	EE	0.388	0
18	VV	0.467	0
19	RR	0.847	0
20	OU	1.024	1
21	LL	3.600	5

[1] Hazard matrix elements range from 0.058 to 3.600.

Table A5. Nature of the Perception Errors

E[a]	K[b]	Challenge	Response Choices				
9	1	OU	VV	OU	RR	AA	ZZ
10	1	LL	OU	VV	LL	RR	ZZ
10	5	LL	OU	LL	RR	VV	ZZ
10	6	LL	OU	LL	RR	VV	ZZ
10	7	LL	OU	LL	RR	VV	ZZ
10	8	LL	OU	LL	RR	VV	ZZ
14	1	OO	NN	OO	AH	OU	AW

[a]The original numerical code for the challenge sound is E.

[b]The sample number of the challenge sound is K.

Table A6. Cochlear First-Moment Statistics

Phoneme	Max	Min	Ave	Dev
OH	-63.84	-77.42	-73.59	2.09
EE	-30.14	-48.38	-39.78	3.78
EH	22.23	8.43	15.11	4.41
SS	91.84	81.91	86.54	2.96
AA	13.09	- 4.63	4.32	4.32
ZZ	-14.96	-46.52	-33.70	5.68
AY	10.70	-12.50	- 1.93	7.11
FF	79.42	70.25	75.64	2.10
OU	-50.50	-71.35	-64.38	4.21
LL	-69.38	-83.98	-77.20	3.42
KH	71.58	39.63	63.40	7.61
AH	- 2.44	-23.05	-13.28	5.73
RR	-26.34	-56.40	-38.98	9.25
OO	-76.40	-93.03	-91.05	2.62
AW	-38.10	-57.23	-46.11	4.06
SH	92.80	87.03	90.74	1.24
VV	-48.75	-76.19	-63.08	5.34
II	9.92	-29.11	-11.95	11.51
ZH	- 2.63	-39.76	-27.73	9.47
UH	-30.14	-55.07	-38.05	6.53
NN	-65.47	-88.90	-83.71	4.21

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Development of the artificial cochlea was reported under previous grant. Work on this grant was oriented at testing the cochlea for automatic speech recognition. Use of the HP-9830 indicated that it is a good machine for low budget ASR if ways can be found to slow down input data rate. Data was taken on the 21 prolongable phonemes using the cochleas model. One surprise noted was a finding of high consistency in the first moment of the cochleas response to a given phoneme, irrespective of pitch. Much more analysis of data remains to be done; however, funding of this work has been

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20. Abstract

discontinued due to other priorities.